Nature of Seismic Gaps and Foreshocks

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In this report we will discuss several problems on seismic gaps from the point of view of identifying ready-to-break gaps.

1. Seismic gaps at subduction zones

Seismic gaps are usually identified as a spatial gap of activity along subduction zones. Whether the identified gap is seismic or aseismic (i.e. permanent gap) has an important bearing on the problem of capturing a gap earthquake in the near future. For example, most gaps to the north of 40°N in the western Pacific region seem to be seismic, but the nature of the gaps to the south is unclear (Figure 1). For the region between 36°N and 37°N, Abe (1977) concluded that there was no major earthquake in this region at least for the past 800 years. The most recent activity in this region is represented by the 1938 Shioya-Oki earthquake sequence. Although the magnitudes of the earthquakes in this sequence are close to 8, they are significantly smaller than those to the north of 40°N.

Further to the south along the Izu-Bonin-Mariana arc, there is no record of large shallow earthquakes. Although earthquake data go back only several decades, historical tsunami records strongly indicate a lack of great shallow earthquakes in this region at least for the past several hundred years.

Several possibilities have been suggested for the lack of great earthquakes: decoupling between the oceanic and continental lithospheres (Kanamori, 1971, 1977), hang-up of subduction caused by buoyant oceanic lithospheres (Vogt, 1973; Kelleher and McCann, 1976) and receding upper-plates (Uyeda and Kanamori, 1978). In order to distinguish seismic gaps from aseismic gaps, it is important to make detailed studies of sea-bottom topography of the subducting

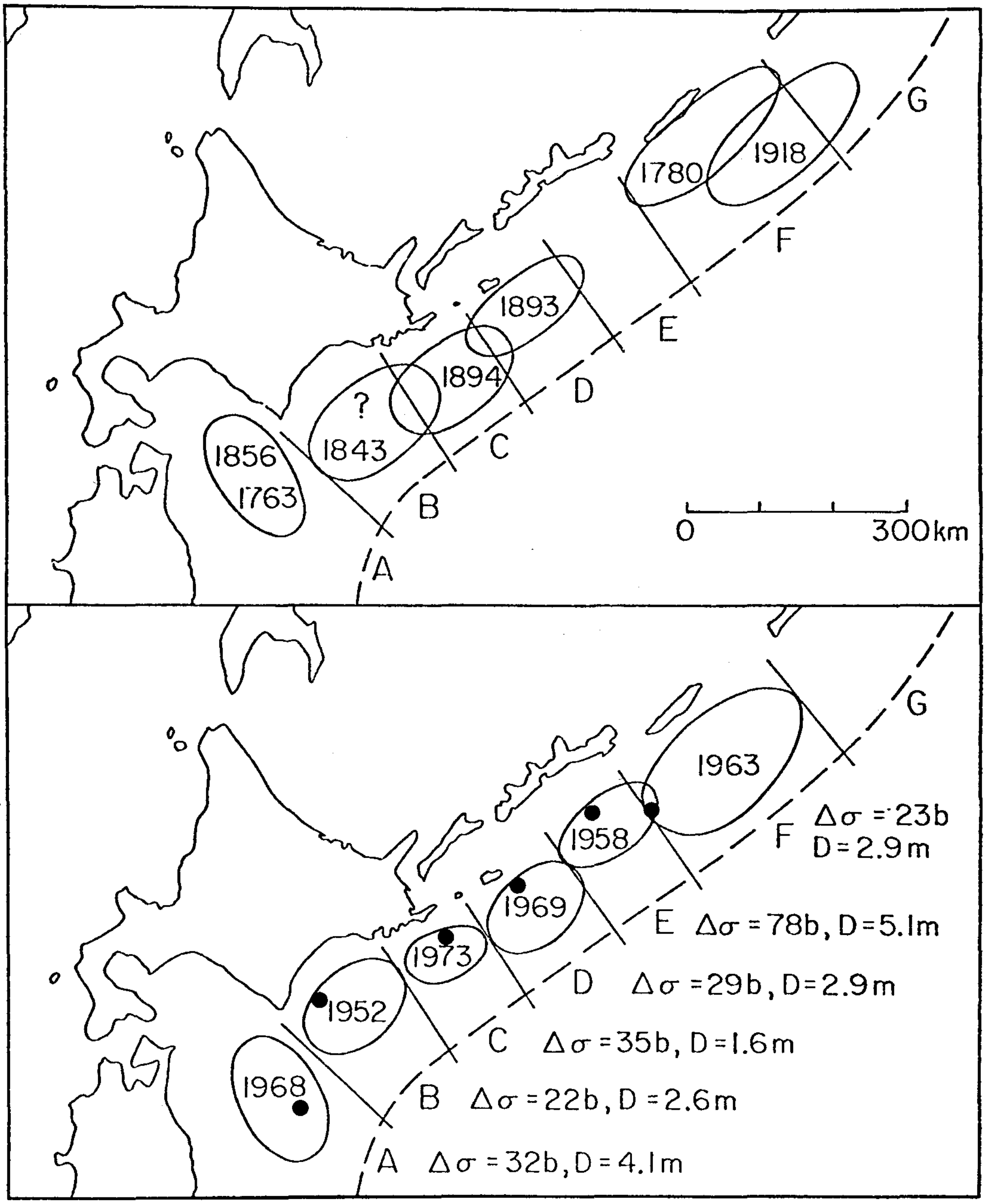


Figure 1a. Seismic fault zones in the northwestern Pacific. The upper figure shows a sequence from 1763 to 1918. Note the missing event in E. The lower figure shows the last sequence (after Fukao and Furumoto, 1978).

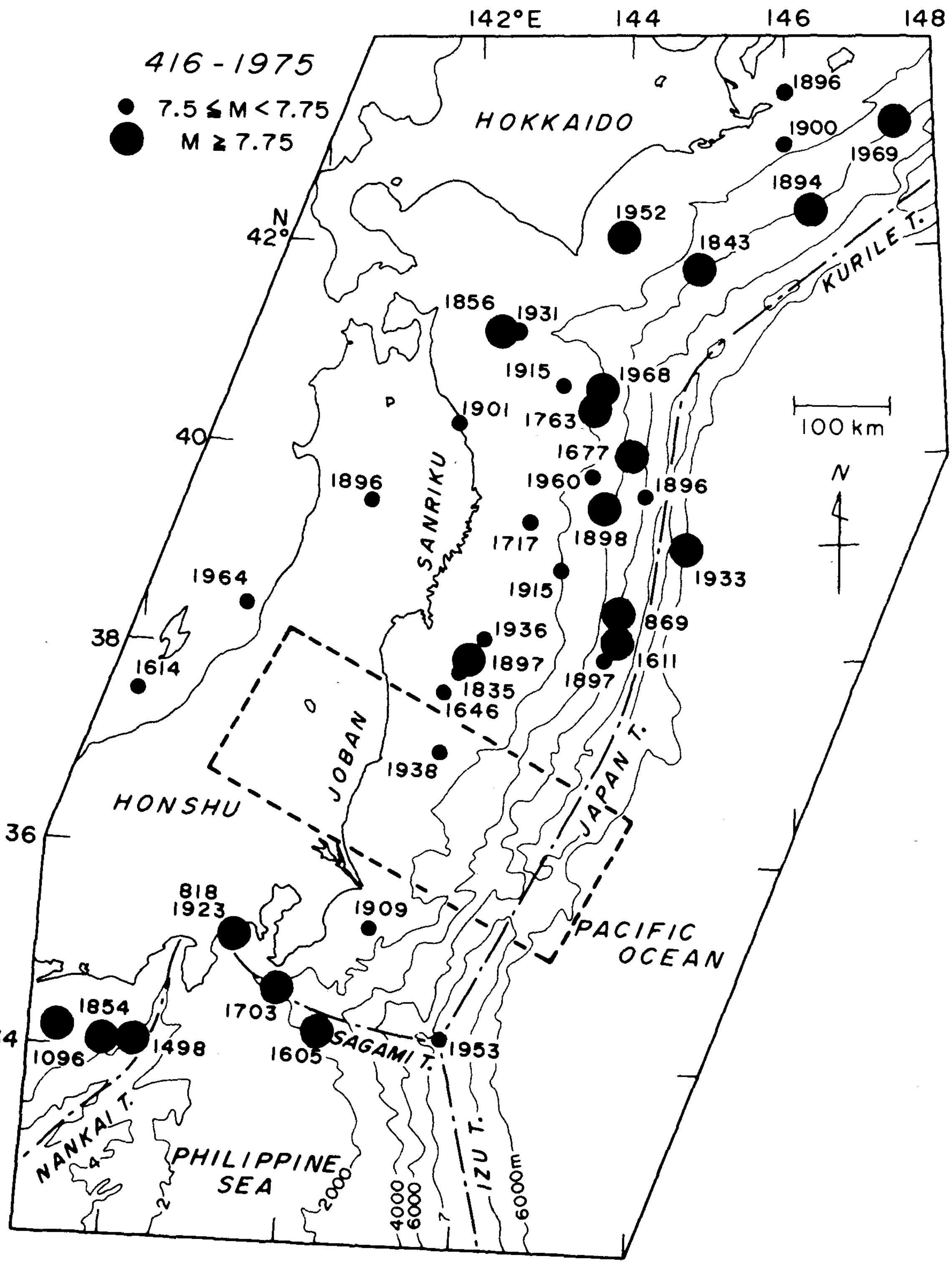


Figure 1b. Epicenters of large earthquakes in and around northern Japan and Izu-Bonin trench to the south of 38°N (after Abe, 1977).

lithosphere and the mechanisms of earthquakes in the adjacent regions. The former would provide information on the buoyancy of the oceanic lithosphere, and the latter, the nature of the lithospheric coupling.

It is also important to note that a recent study of Fukao and Furumoto (1977) suggests that the 1958 Kurile islands earthquake (Figure 1) occurred in a region which remained as a gap during the previous cycle of activity. This result indicates that the fracture strength along a subduction zone varies substantially and the repeat time of great earthquakes may vary greatly from place to place even along the same arc.

Another interesting feature related to the spatial transition from seismic to aseismic gap in the north-western Pacific is the foreshock activity. The 1963 and the 1969 Kurile islands earthquakes had pronounced foreshock activity, and the 1973 Nemuro-Oki earthquake had two teleseismically located foreshocks (Figure 2). However, the 1952 and the 1968 Tokachi-Oki earthquakes which are located between the seismic and aseismic arcs did not have pronounced foreshock activity (see Figure 1). This difference probably reflects the difference in the mechanical property of the subduction zone. Since foreshock activity is one of the most definitive precursors, this difference is important for designing an experiment for capturing a large gap earthquake.

Many great earthquakes at subduction zones were preceded by pronounced foreshock activities (e.g. 1963 Kurile islands earthquake, 1965, Rat Island earthquake, 1960 Chilean earthquake) (Mogi, 1969). These foreshock activities are relatively short-term (days and weeks) (see Figure 2b) but it is not clear whether they represent a distinct clustering of events within the individual gap during the inter-seismic period or not. The existing earthquake

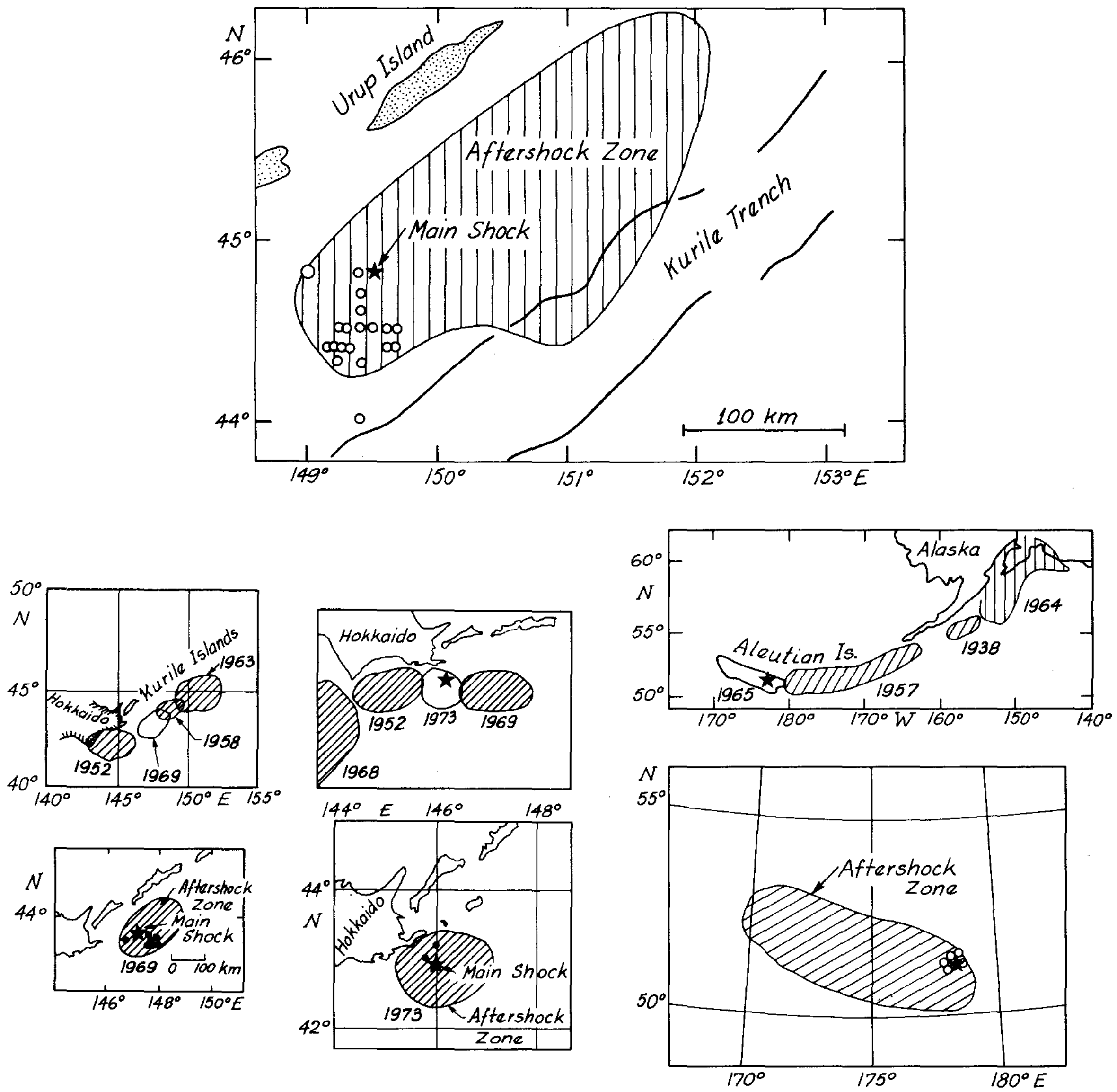
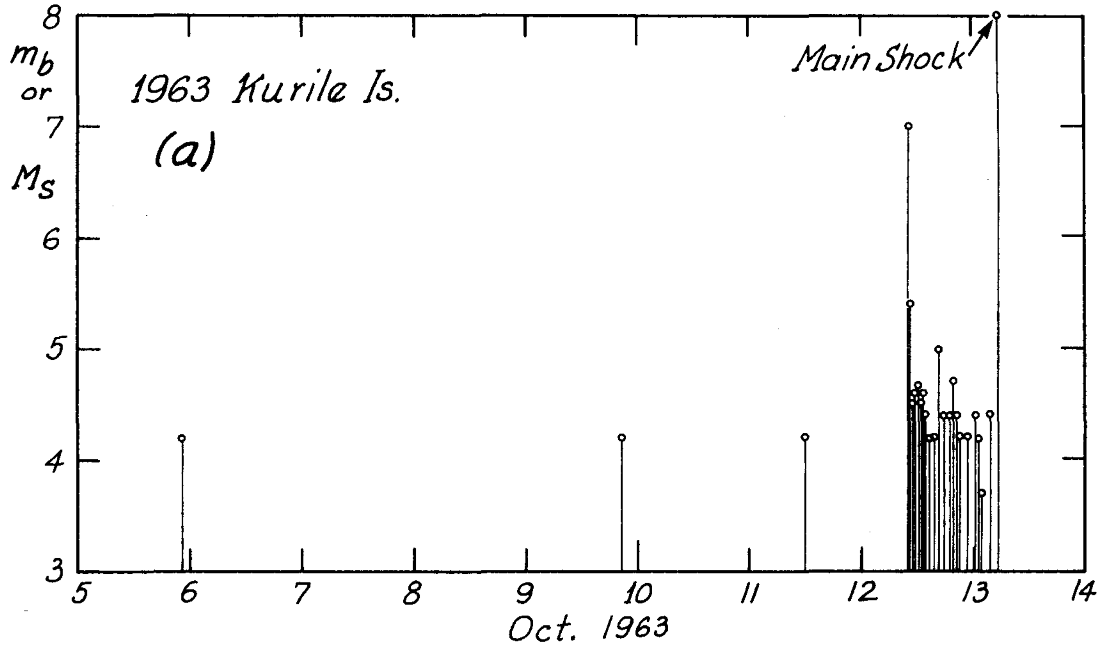


Figure 2a. Foreshocks of the 1963 Kurile Islands, the 1969 Kurile Islands, the 1973 Nemuro-Oki earthquake, and the 1965 Rat Islands earthquake.



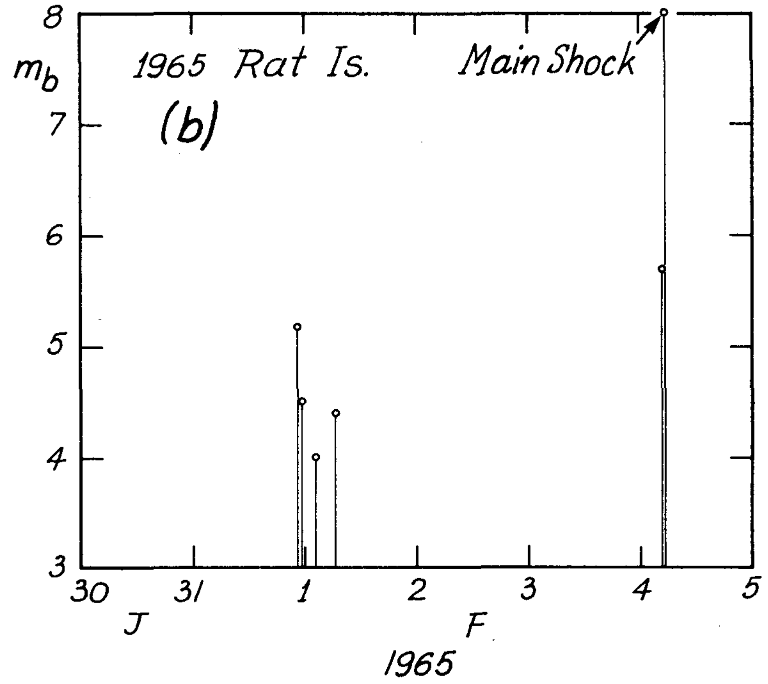


Figure 2b. Time sequence of the foreshocks of the 1963 Kurile Islands earthquake (a) and the 1965 Rat Islands earthquake (b).

catalogs are too incomplete and inaccurate to resolve this problem.

2. Other seismic gaps

Wesson and Ellsworth (1973) and Kelleher and Savino (1975) discussed seismicity prior to several subduction zone, as well as non-subduction zone earthquakes. Here we will focus on the 1971 San Fernando earthquake and the 1952 Kern County earthquake because these earthquakes have fairly complete earthquake data during the pre-seismic period.

Figures 3 and 4 show the seismicity pattern prior to the 1971 San Fernando earthquake. It appears that a quiet period from 1965 to 1968 (gap) was followed by foreshock activity from 1969 to 1971. This pattern is similar to that found for several other earthquakes. However, the space-time plot (Figure 3) shows that a similar "gap-foreshock" pattern is seen at least three times prior to 1965 (i.e., 1940 to 1949, 1950 to 1956, and 1957 to 1965), and, therefore, the pattern seen immediately before the San Fernando earthquake may not be a unique one. It is unclear whether the gap during the period from 1965 to 1969 has any significance as precursor. However, the foreshocks that occurred during the period from 1969 to 1970 have distinct wave forms (Ishida and Kanamori, 1978a). This feature, together with the seismicity pattern may be a more useful diagnostic pattern of a ready-to-break gap.

Figure 5 shows the seismicity prior to the Kern County earthquake of 1952 (Ishida and Kanamori, 1978b). Figure 5a, which includes a substantial part of the data represents the pattern already suggested by Wesson and Ellsworth (1973) and Kelleher and Savino (1975). A large part of the fault plane seems to have been seismically quiet for nearly 15 years before the Kern County earthquake. During this period the activity near the epicentral area was very high. As shown by Figures 5b and 5c, this activity became very low during the two-year period from

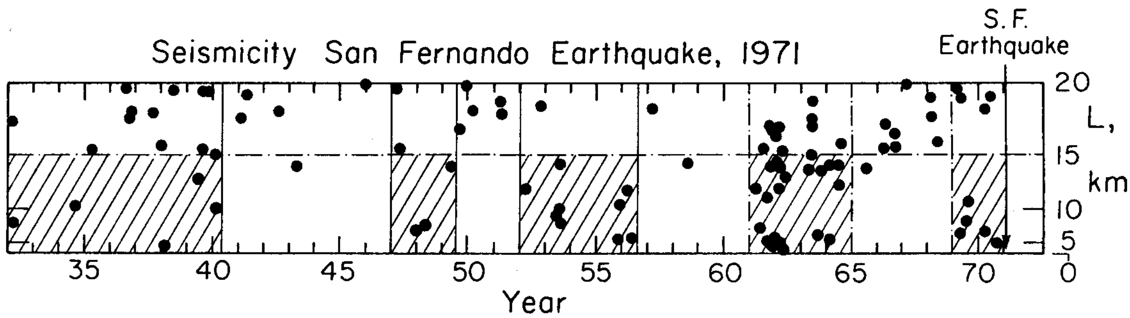


Figure 3. Space-time plot of the seismicity before the 1971 San Fernando earthquake (Ishida and Kanamori, 1977).

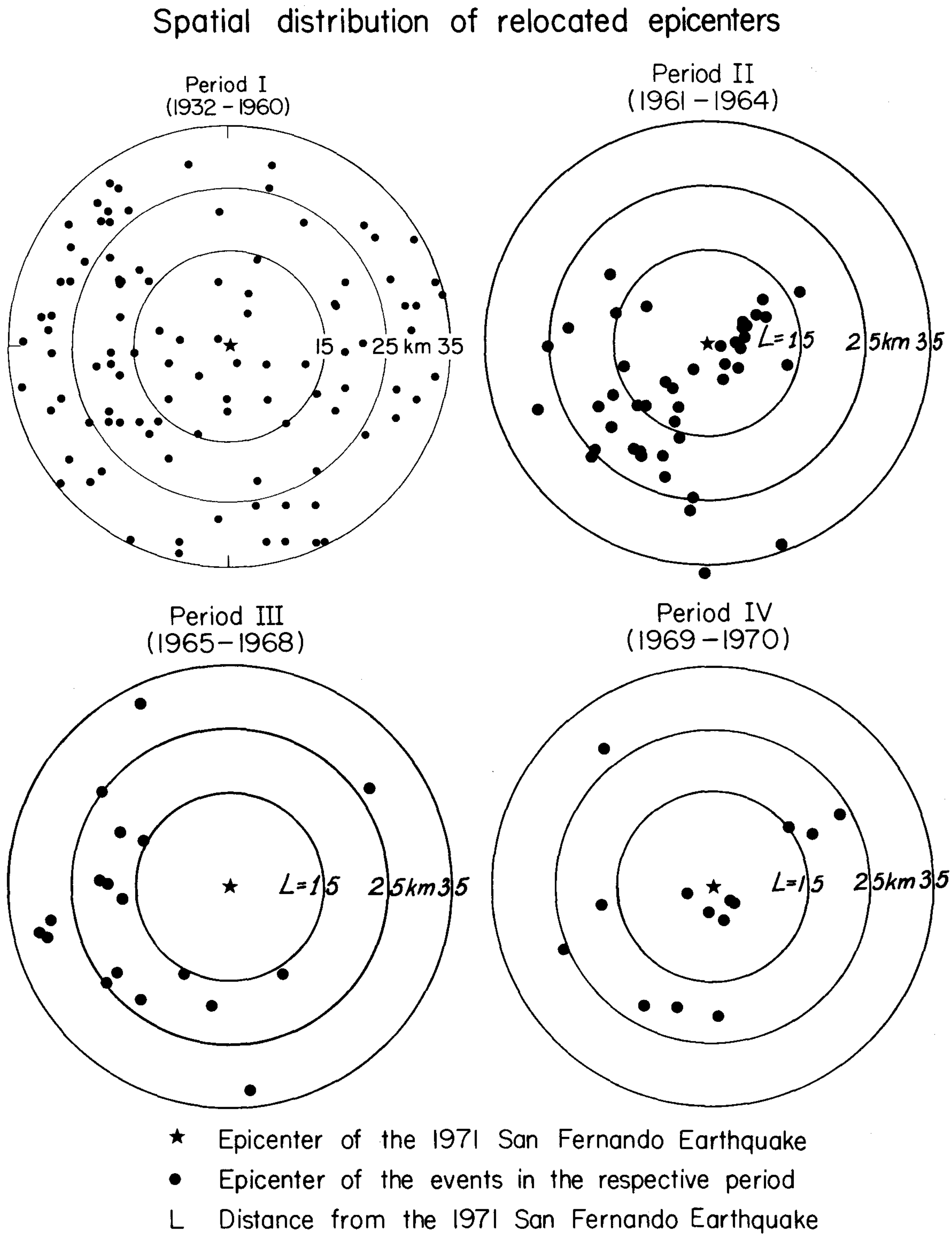


Figure 4. Distribution of epicenters before the 1971 San Fernando earthquake for four periods (Ishida and Kanamori, 1978a)

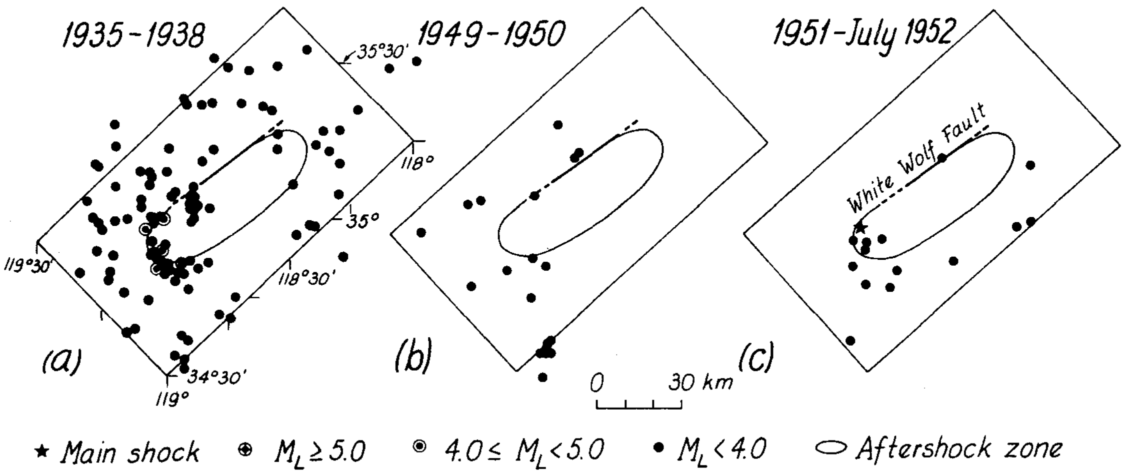


Figure 5. Distribution of epicenters before the 1952 Kern County earthquake for three periods (Ishida and Kanamori, 1978b).

January 1949 to December 1950. This low activity was followed by a clustering of events near the main shock epicenter which may be considered to be foreshock activity of the Kern County earthquake. This pattern is very similar to that found for the 1971 San Fernando earthquake. However, a space-time plot (Figure 6) indicates that this pattern of "gap -foreshocks" appeared several times before 1950. Thus, it appears that this pattern alone may be of little use as a definitive seismic precursor, unless the events just before the main shock can be distinguished on the basis of another criterion.

One possibility is that this gap corresponds to that seen prior to large subduction zone events (Kelleher and Savino, 1975) and the activity near the epicentral area corresponds to the foreshock activity immediately before large subduction zone events. If this is the case, the foreshock activity before the Kern County earthquake is considered to have lasted for at least 20 years. In this case, the usefulness of foreshock activity for practical earthquake prediction is questionable, unless another criterion is used to distinguish immediate foreshocks from the rest.

3. Discussion

For the purpose of capturing a large earthquake, it is essential to identify a gap which is most likely to break in ten years or so. When a gap in seismic activity is found on the basis of geological data and historical earthquake catalog (e.g., Suruga Bay gap, Oaxaca gap (Ohtake *et al.*, 1977)), it is important to examine whether it is a seismic gap or a permanent gap. Even if the gap is identified as a seismic gap, geological and historical data alone cannot provide information regarding when it is going to break. For

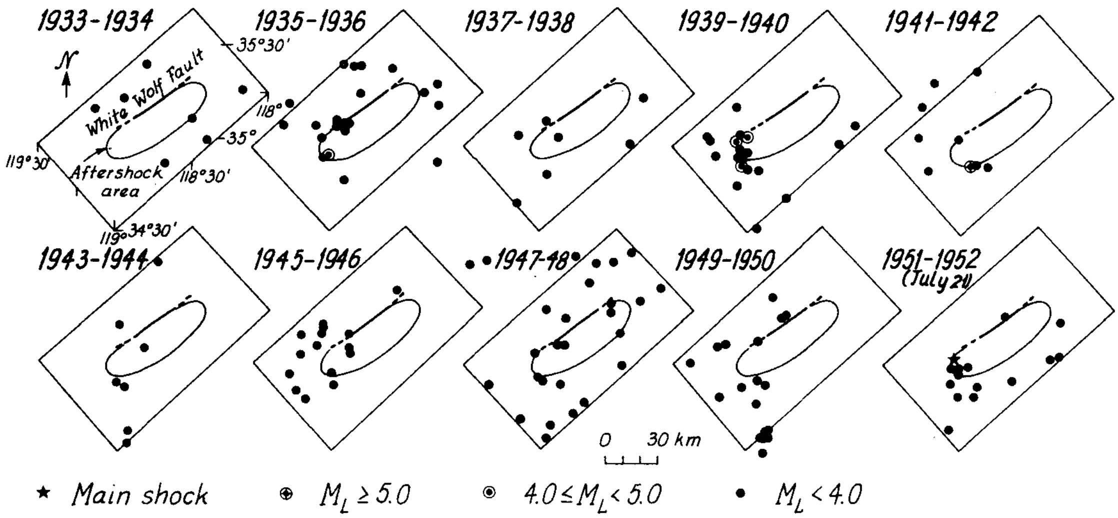


Figure 6. Seismicity in the epicentral area of the 1952 Kern County earthquake as a function of time. Each figure represents seismicity for a consecutive two-year period, except the last figure that represents the period from January 1951 to July 1952 (Ishida and Kanamori, 1978b). Aftershock area (after H. Benioff et al., 1953). White Wolf fault (after B. Gutenberg, 1955).

very large ($M_s \geq 8$) earthquakes, the repeat time is usually longer than 100 years, with very large uncertainty, so that a simple statistical estimate is too uncertain to be useful for identifying a ready-to-break gap. For smaller events ($M_s \sim 7$), the repeat time may be short enough to make statistical approach useful (e.g. the New Hebrides). However, the source size of $M_s \sim 7$ event is about 50 km so that it is more difficult to capture them than $M_s \geq 8$ events whose dimension is 200 km or larger.

Short-term precursors such as anomalous crustal deformation and foreshock activity appear most useful, if they occur at all, for identifying a ready-to-break gap. Although geodetic data are very sparse, foreshock activity has been observed for many gap events. Since the time of occurrence of an earthquake is ultimately controlled by distribution of stress on the fault plane, it is essential to know how spatio-temporal distribution of stress on the fault plane changes. In view of the lack of a simple method for direct determination of stresses at depths, it appears most promising to use spatio-temporal variation of seismicity (including spectra, wave form, mechanism etc.) in seismic gaps and in the surrounding areas for determining whether the gap is soon-to-break or not.

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